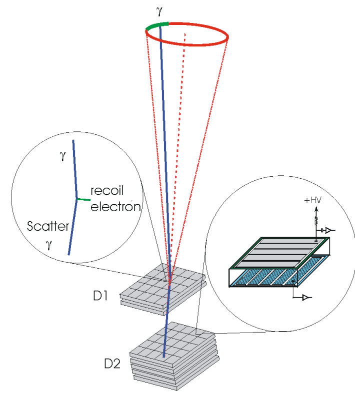
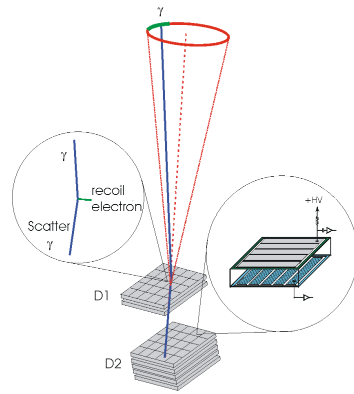


Compton Principles and Multiple Compton Scatter Technique

J. D. Kurfess
Naval Research Laboratory

OUTLINE



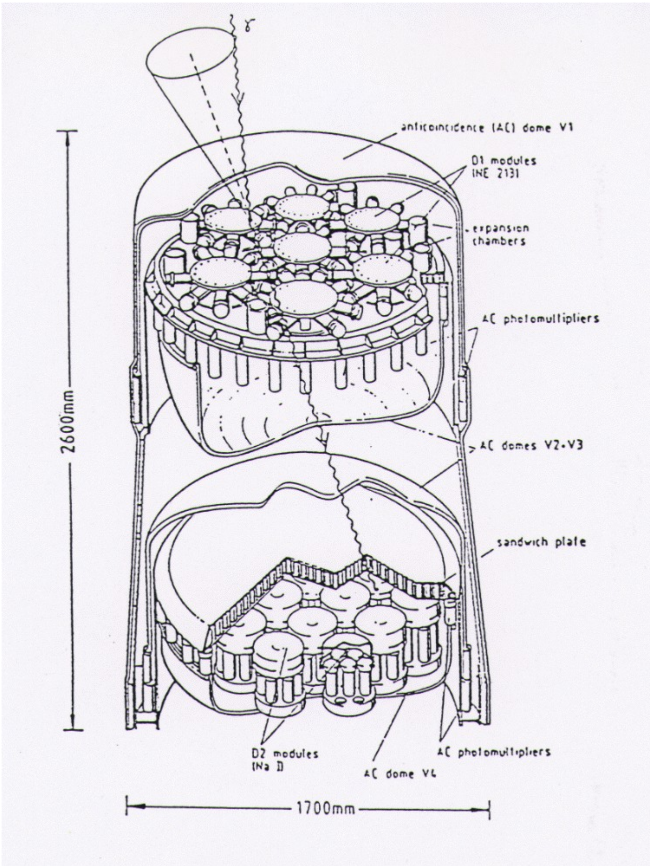
Conventional Compton Telescopes

- Efficiency
- Energy resolution
- Angular resolution

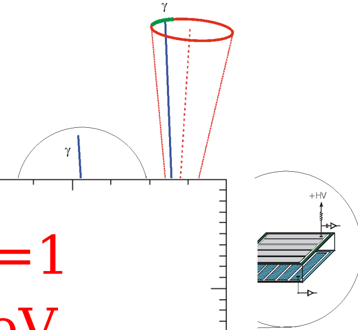
Multiple Compton Telescope

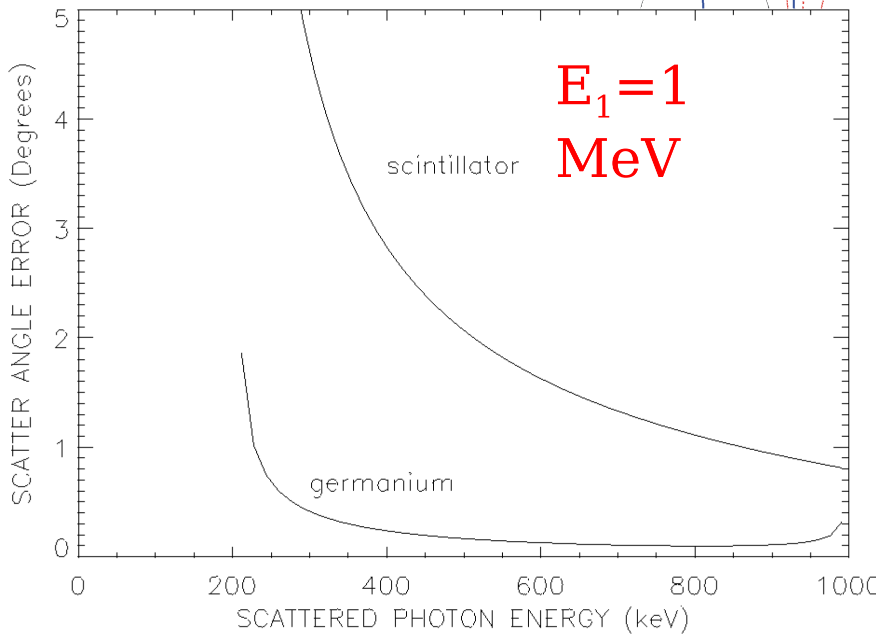
- Concept
- Energy resolution
- Angular resolution
- Doppler Broadening
- Background reduction
- Polarization

Compton Scattering



Schematics of COMPTEL





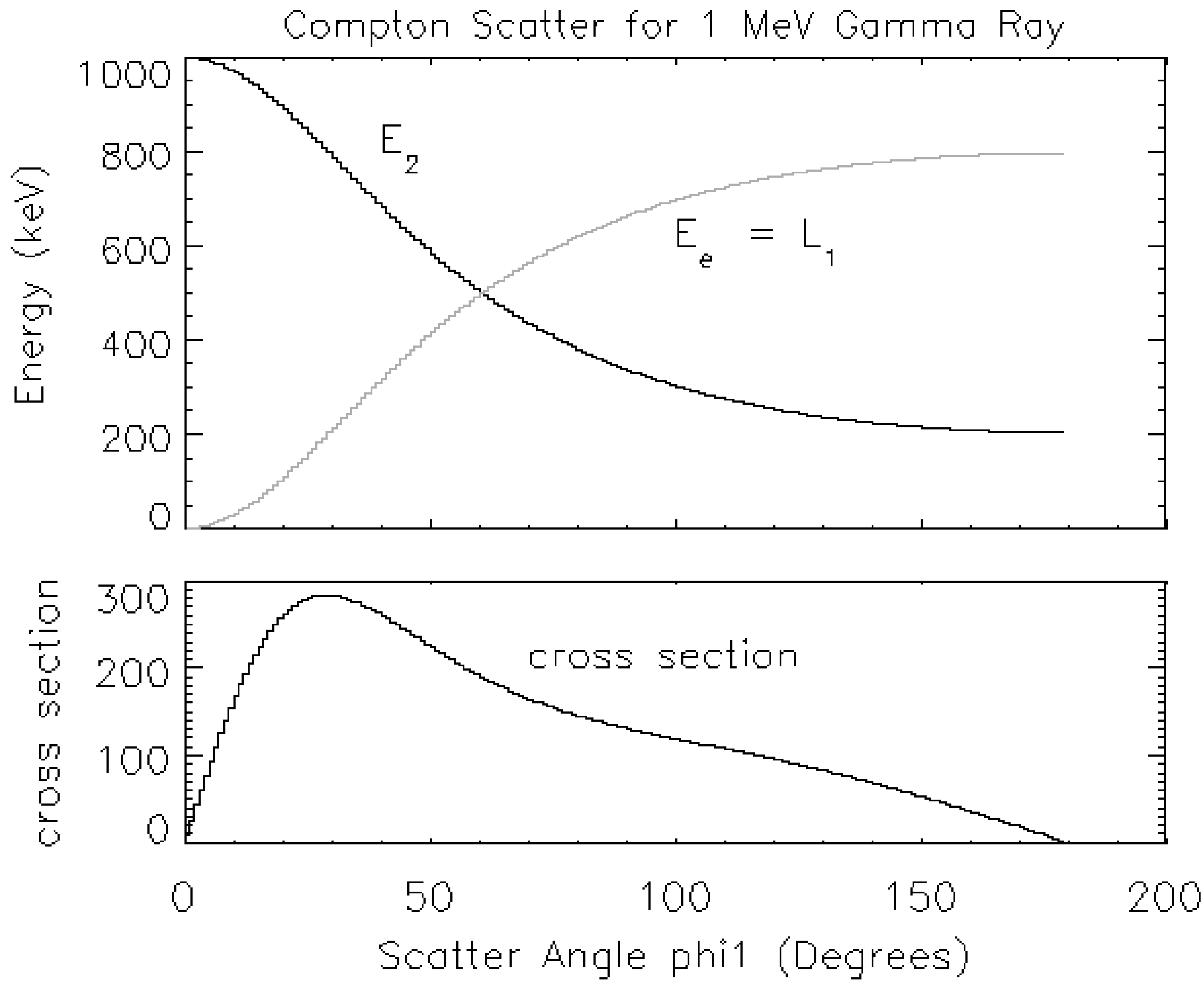
E_1=1 MeV

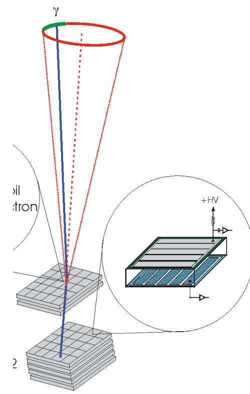
$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right)$$

Comptel efficiency ~ 1%

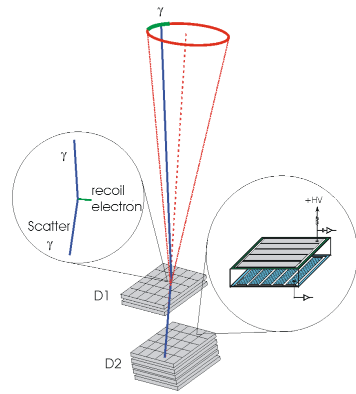
$$\delta\phi = \frac{m_e c^2}{\sin\phi} \left[\frac{\delta E_u^2}{E_1^4} + \delta E_l^2 \left(\frac{1}{E_2^2} - \frac{1}{E_1^2} \right)^2 \right]^{1/2}$$

Compton Scattering at 1 MeV





Directions for Improvement



Increase Efficiency

- More Compact Design
- Monolithic, Position-sensitive detectors

Energy Resolution

- Solid State Detectors
- Gas Detectors

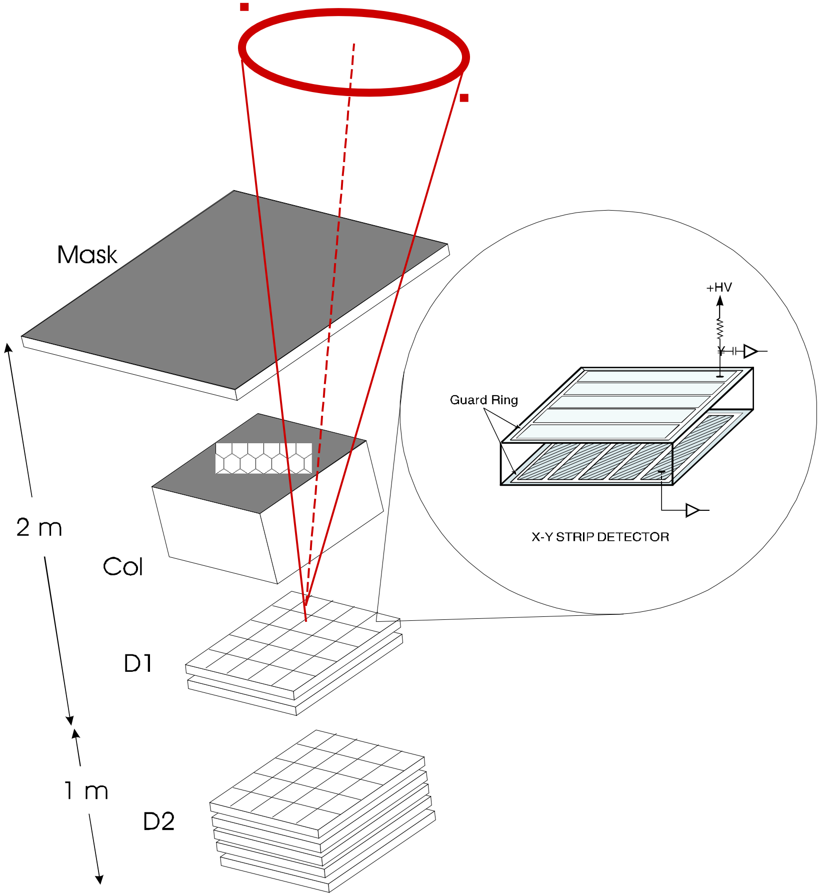
Angular Resolution

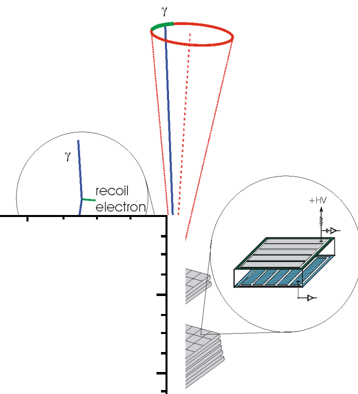
- Position-sensitive detectors
- Electron tracking

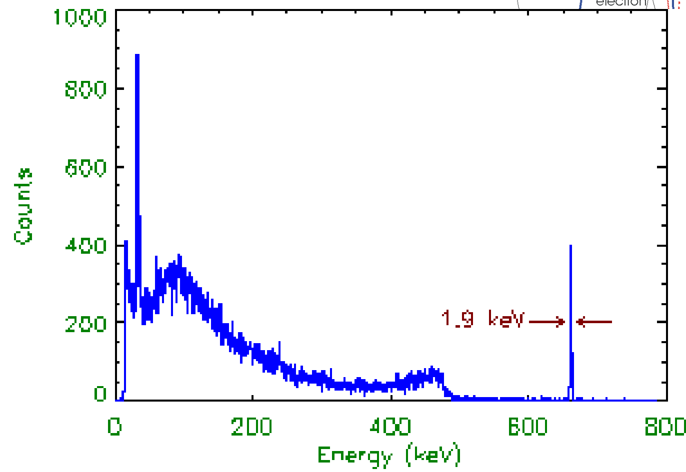
Background Reduction

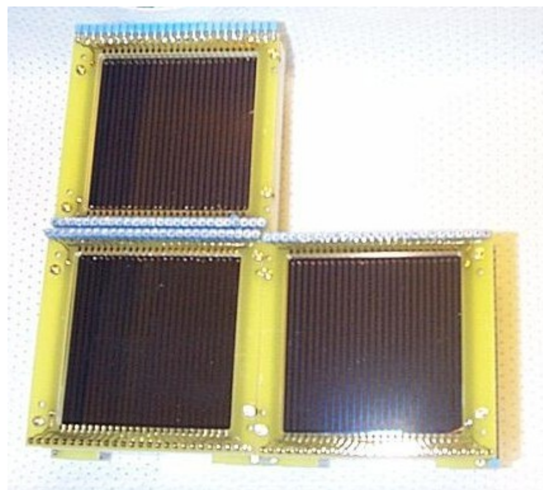
- Electron tracking
- Event reconstruction
- Choice of orbit
- Polarization

High Resolution Compton Telescope







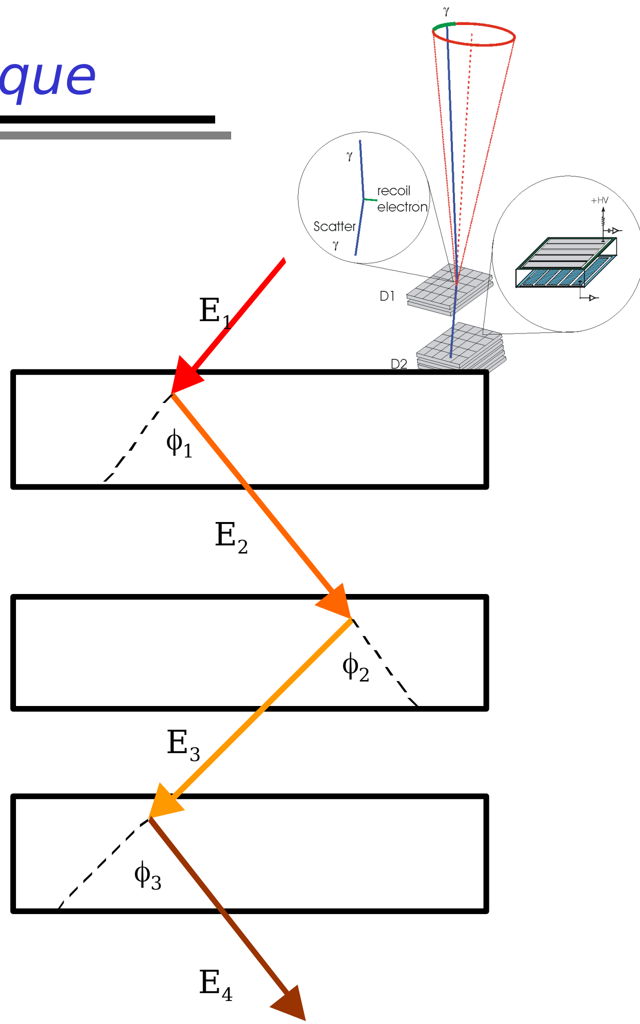


$$\cos\phi_1 = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right); \qquad L_1 = E_1 - E_2$$

$$\cos\phi_2 = 1 - m_e c^2 \left(\frac{1}{E_3} - \frac{1}{E_2} \right); \qquad L_2 = E_2 - E_3$$

$$\cos\phi_3 = 1 - m_e c^2 \left(\frac{1}{E_4} - \frac{1}{E_3} \right); \qquad L_3 = E_3 - E_4$$

$$E_1 = L_1 + \frac{L_2 + \left(L_2^2 + \frac{4 m_e c^2 L_2}{1 - \cos\varphi_2} \right)^{\frac{1}{2}}}{2}$$

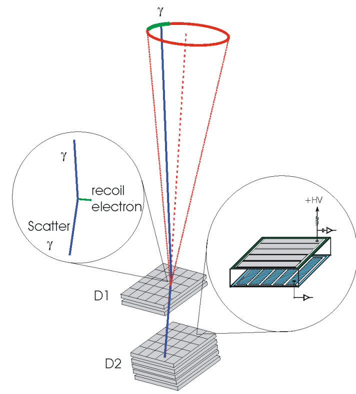


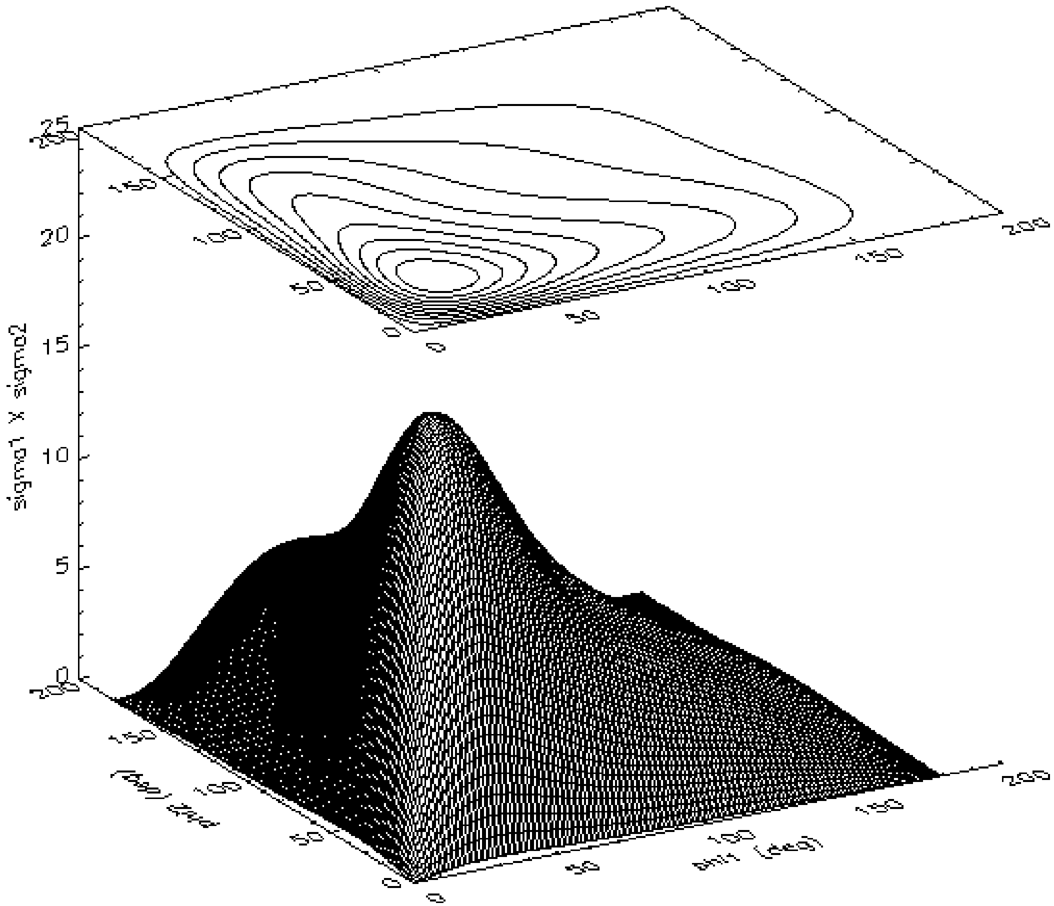
Incident gamma ray energy determined with partial energy loss

- Only three interactions required
- Dramatic improvement in efficiency
- New alternative: Silicon only Compton telescope

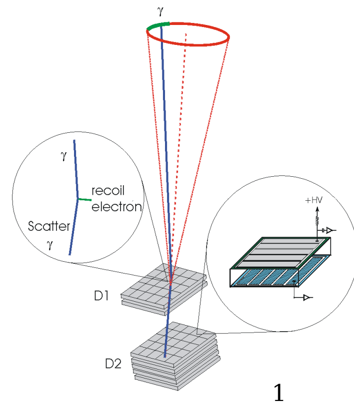
Kurfess et al., Proc. 5th Compton Symp. AIP 510 789 (2000)

Three Gamma Interaction Technique





Differential cross section for double scattering at angles ϕ_1 and ϕ_2

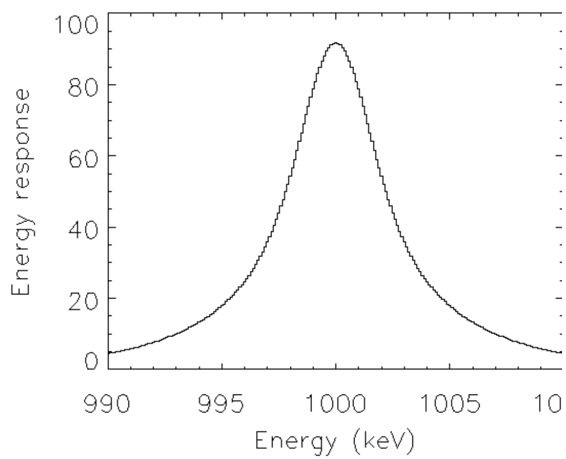


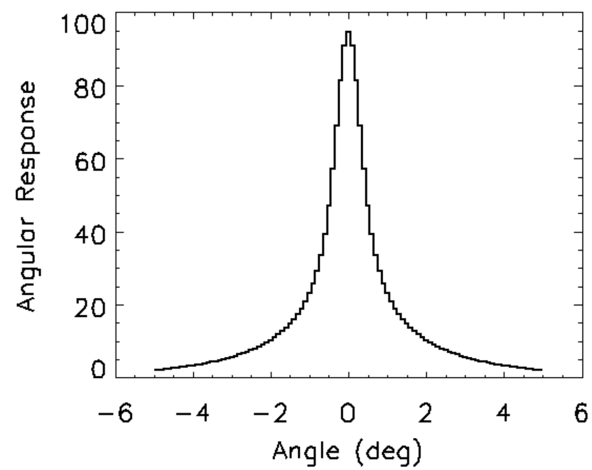
Errors in E_1 and φ_1:

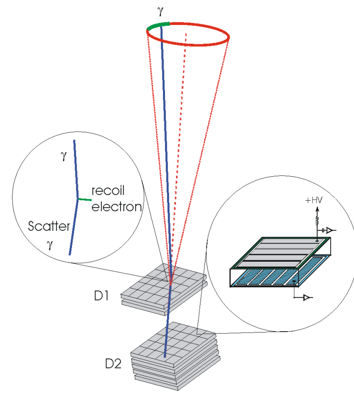
$$dE_1 = \left[dL_1^2 + \left(\left(\frac{1}{2} + \frac{1}{4}\left(L_2^2 + \frac{4mc^2 L_2}{(1-\cos\phi_2)} \right)^{-\frac{1}{2}} \left(2L_2 + \frac{4mc^2}{(1-\cos\phi_2)} \right) \right) \right)^2 dL_2^2 + \left(\frac{\sin\phi_2}{4} \left(L_2^2 + \frac{4mc^2 L_2}{(1-\cos\phi_2)} \right)^{-\frac{1}{2}} \left(\frac{4mc^2 L_2}{(1-\cos\phi_2)^2} \right) \right)^2 d\varphi_2^2 \right]^{\frac{1}{2}}$$

$$d\phi_1 = \frac{mc^2}{\sin\phi_1} \left[\left(\frac{1}{(E_1 - L_1)^2} - \frac{1}{E_1^2} \right)^2 dE_1^2 + \frac{dL_1^2}{(E_1 - L_1)^4} \right]^{\frac{1}{2}}$$

Typical energy and angular response for 3-gamma instrument with detector energy resolution of 2 keV, position resolution of 1mm.







1 m^2 frontal area

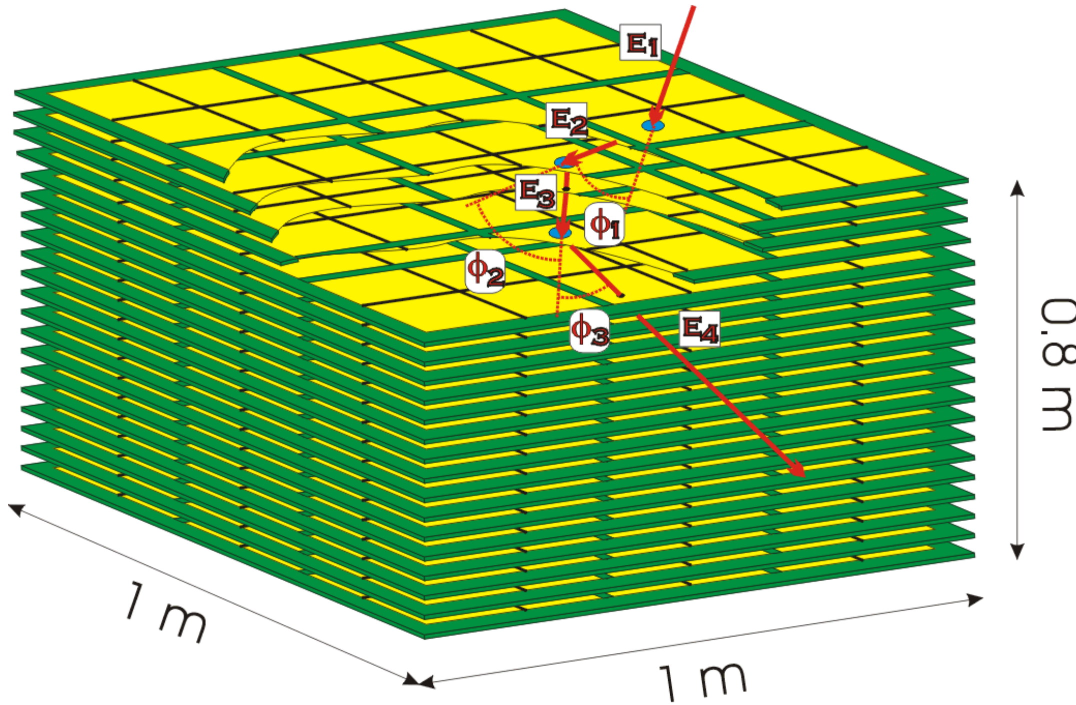
Multiple layers of thick double-sided silicon strip detectors

~ 40 g/cm^2 thick

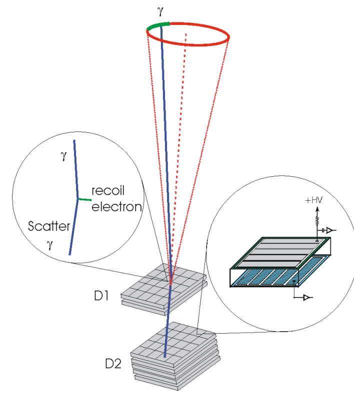
430 kg silicon

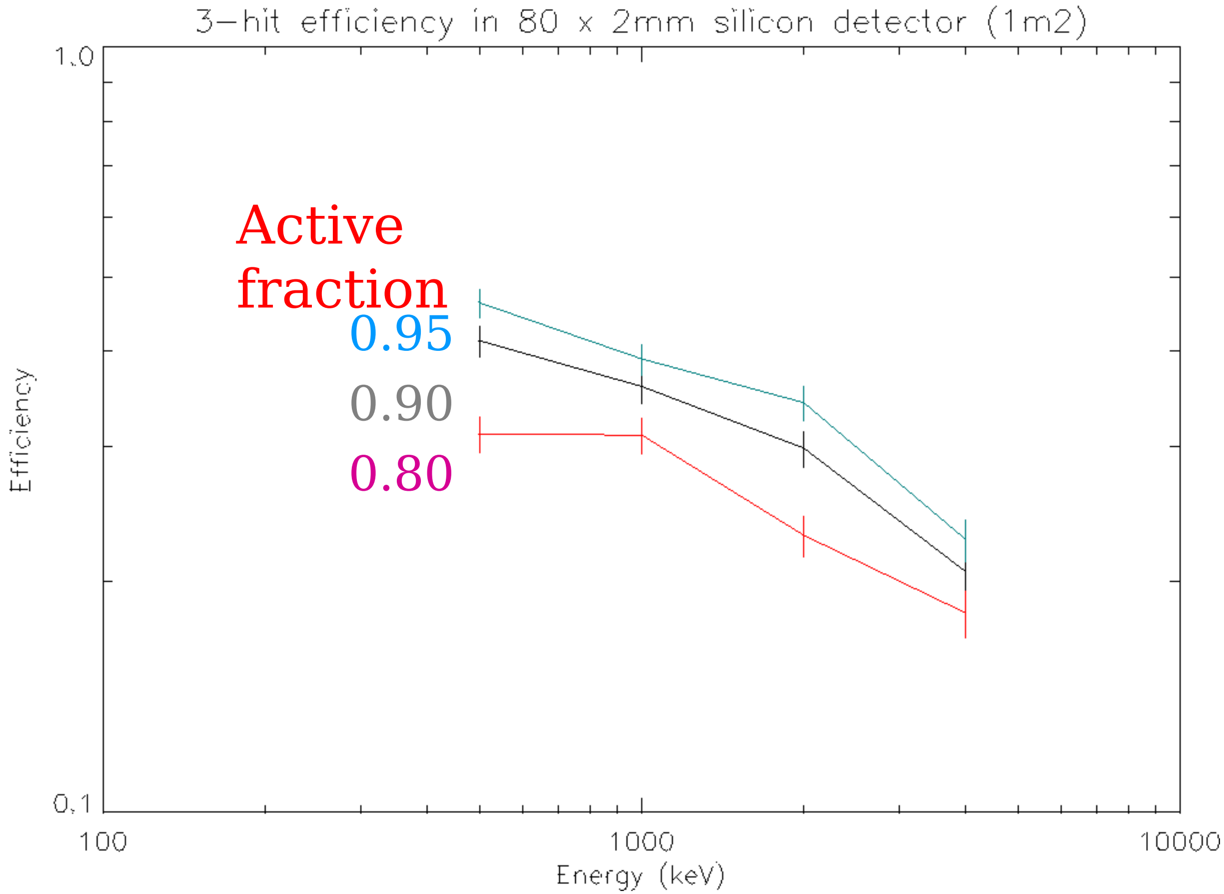
Broad FoV (± 75-90 degrees)

Charged particle anti-coincidence

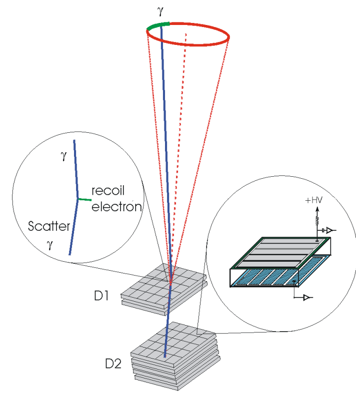


Detection Efficiency vs. active material fraction



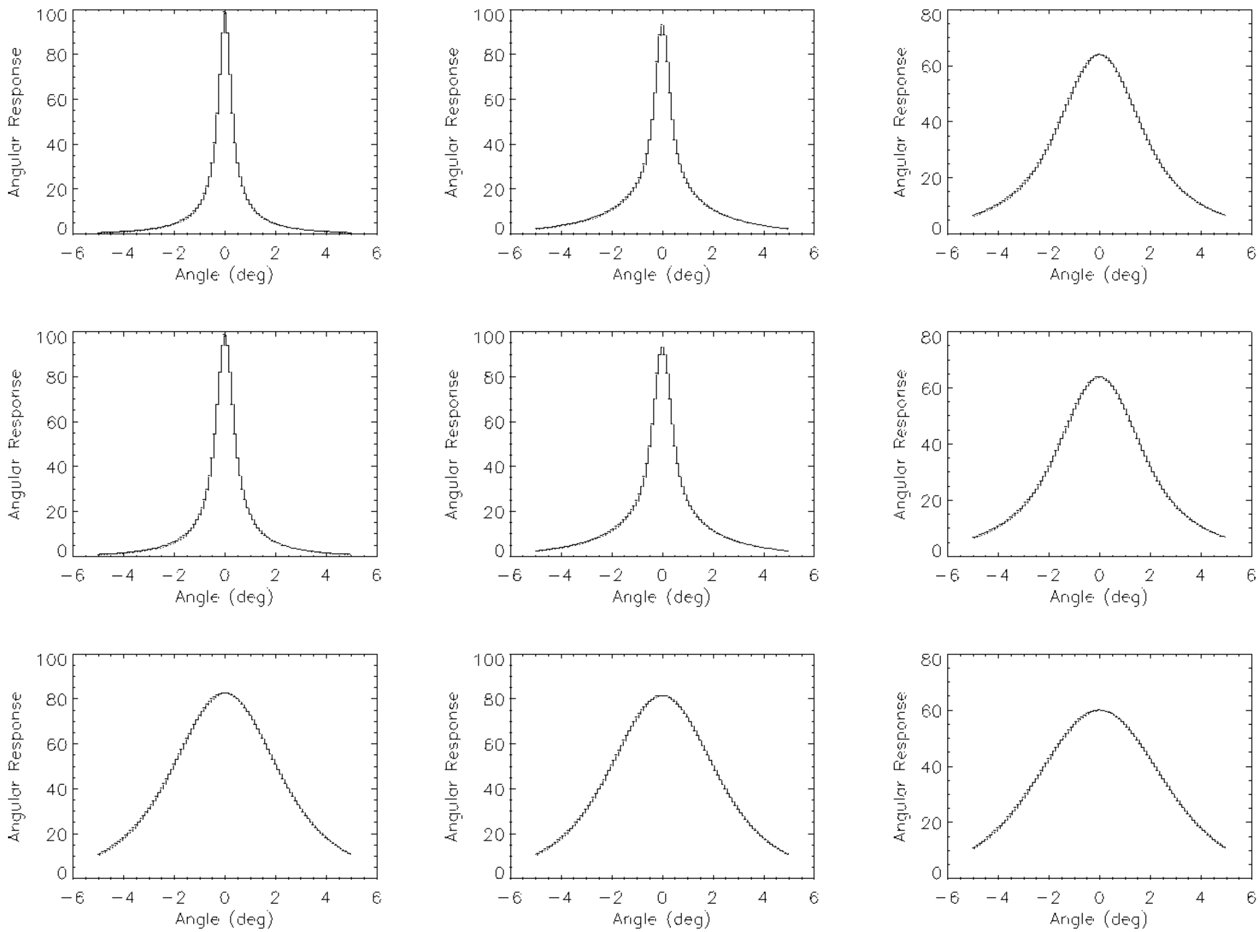


Dependence of 3-γ angular response on detector energy and position resolution



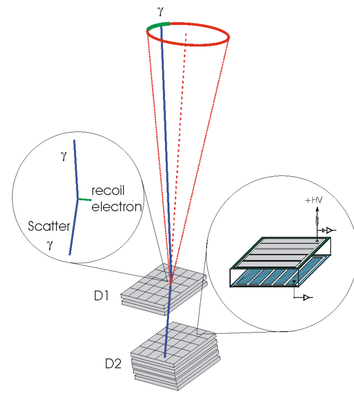
dL=0.1 keV | 1 keV | 10 keV

dx 0.1mm | 1mm | 10mm

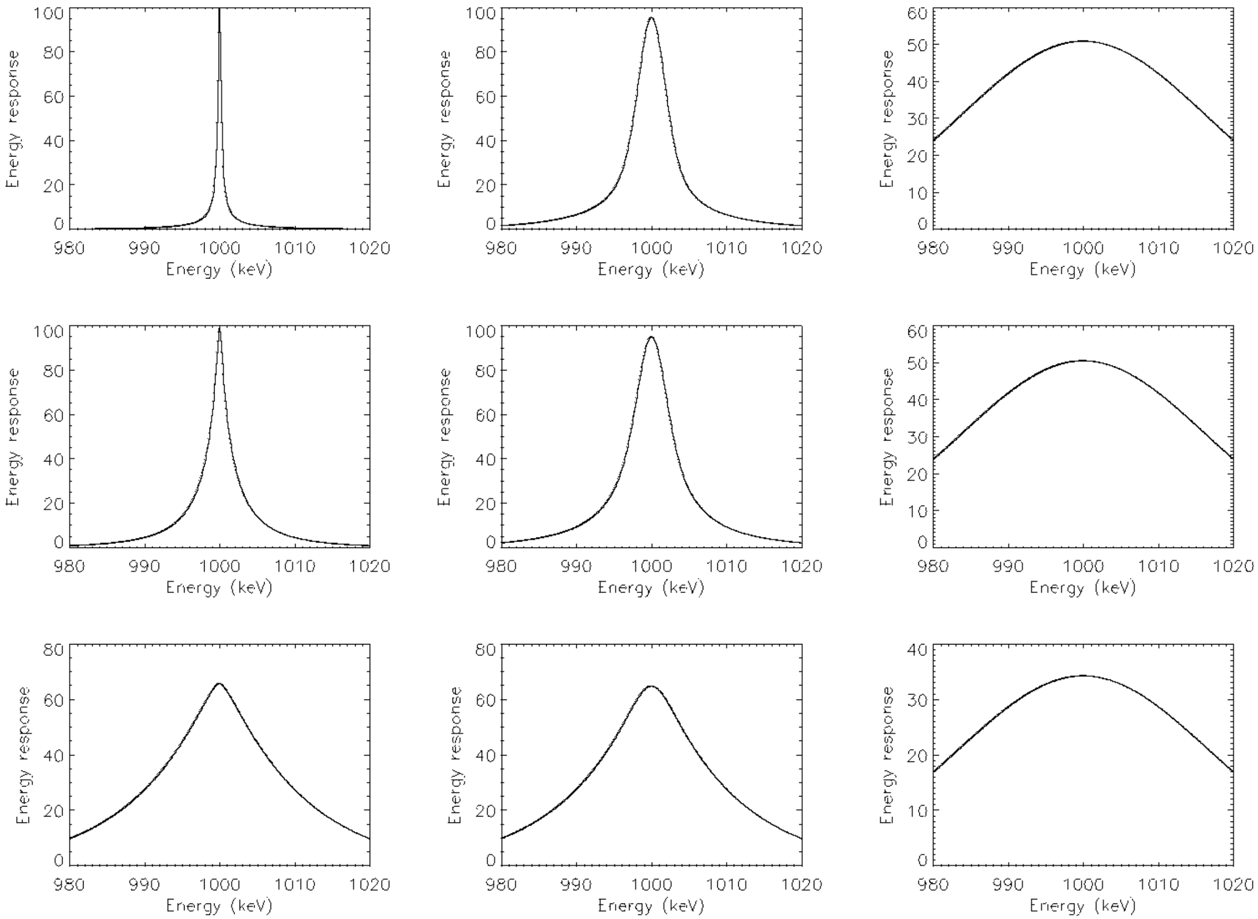


Assumes typical gamma ray pathlength of 15-20 cm (20% fill factor)

Dependence of 3-γ energy response on detector energy and position resolution



dL=0.1 keV | 1 keV | 10 keV



dx

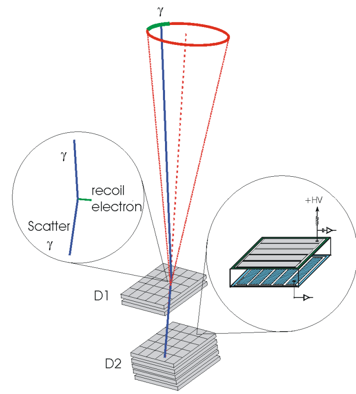
0.1mm

1mm

10mm

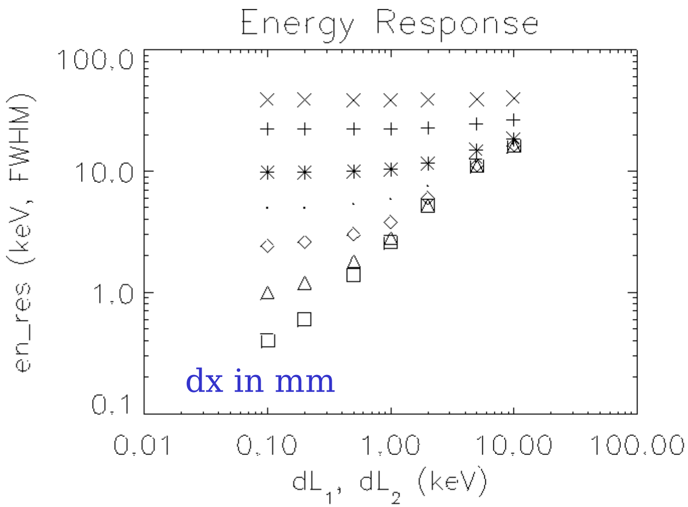
Assumes typical gamma ray pathlength of 15-20 cm (20% fill factor)

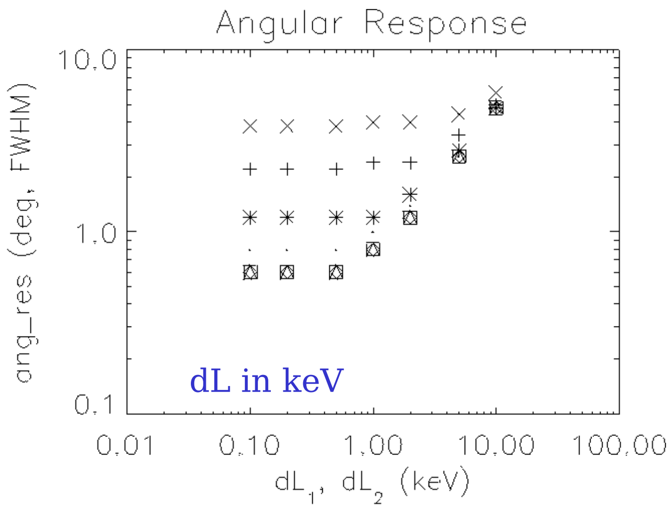
3-scatter energy and angular response vs. energy and position resolution

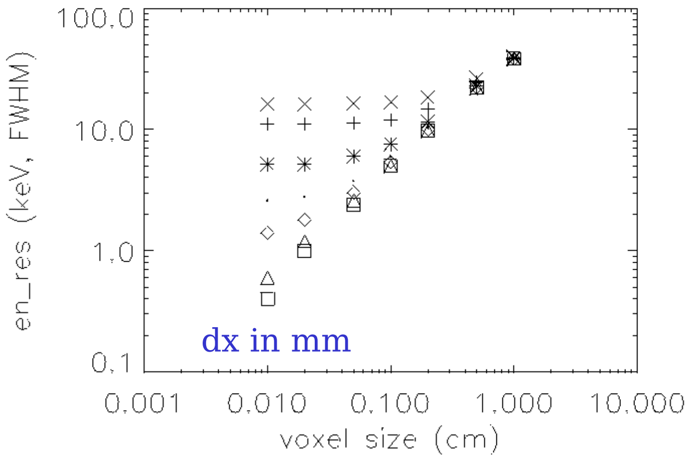


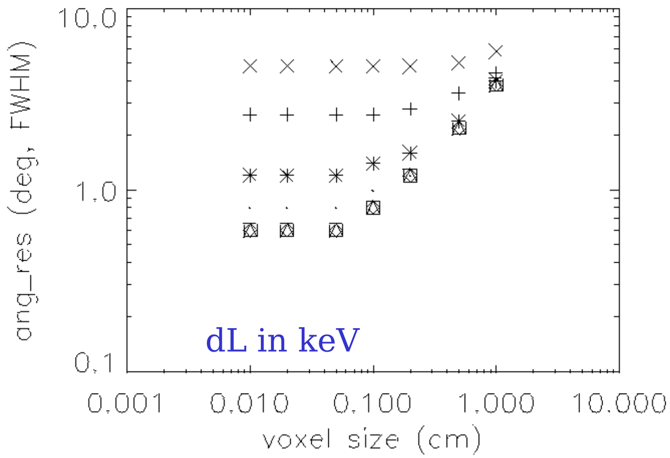
dx is the 3-D position resolution in a detector element.

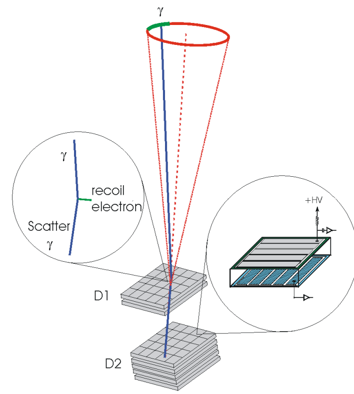
dL is the energy resolution in a detector elemwnt











Standard Compton formulae assume initial electron is at rest.

Shown below is the effect on energy resolution and angular resolution when electron velocity is taken into consideration.

This ‘Doppler’ effect at the first Compton scatter site produces an uncertainty in the angle of the incident gamma ray.

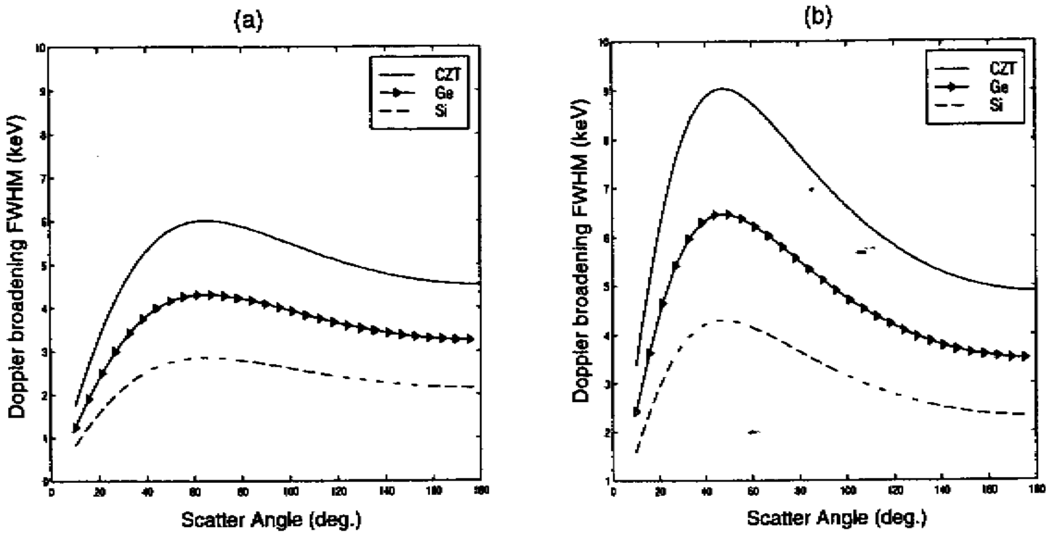
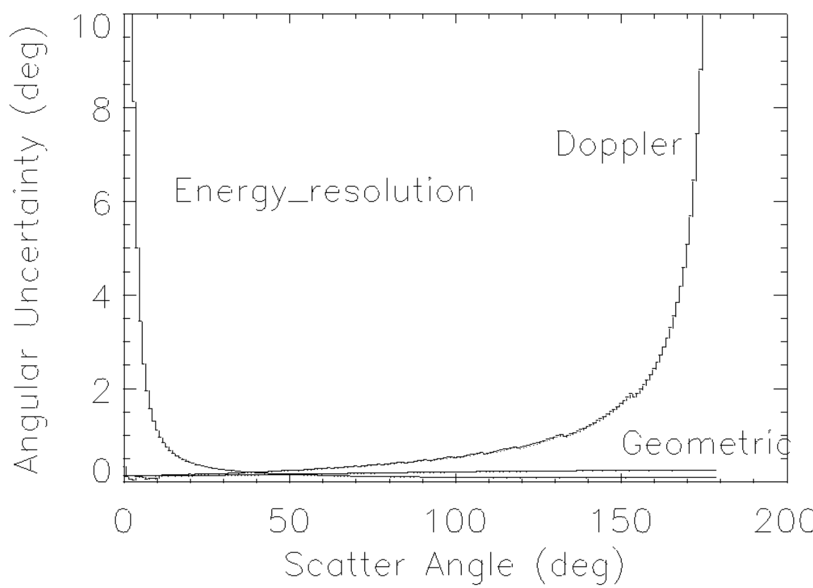
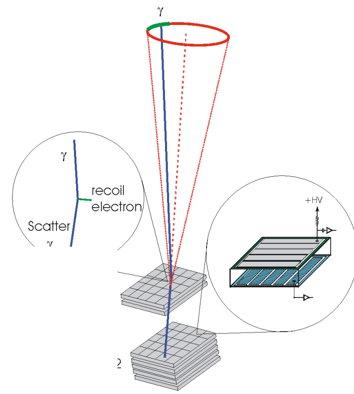


Figure 5. Energy uncertainty due to Doppler broadening effect for (a) 511 keV, (b) 1MeV.

Du et al. SPIE **3768** p. 228 (1999)



Geometric, Doppler, and energy response uncertainty contributions to the angular uncertainty for the incident gamma ray.



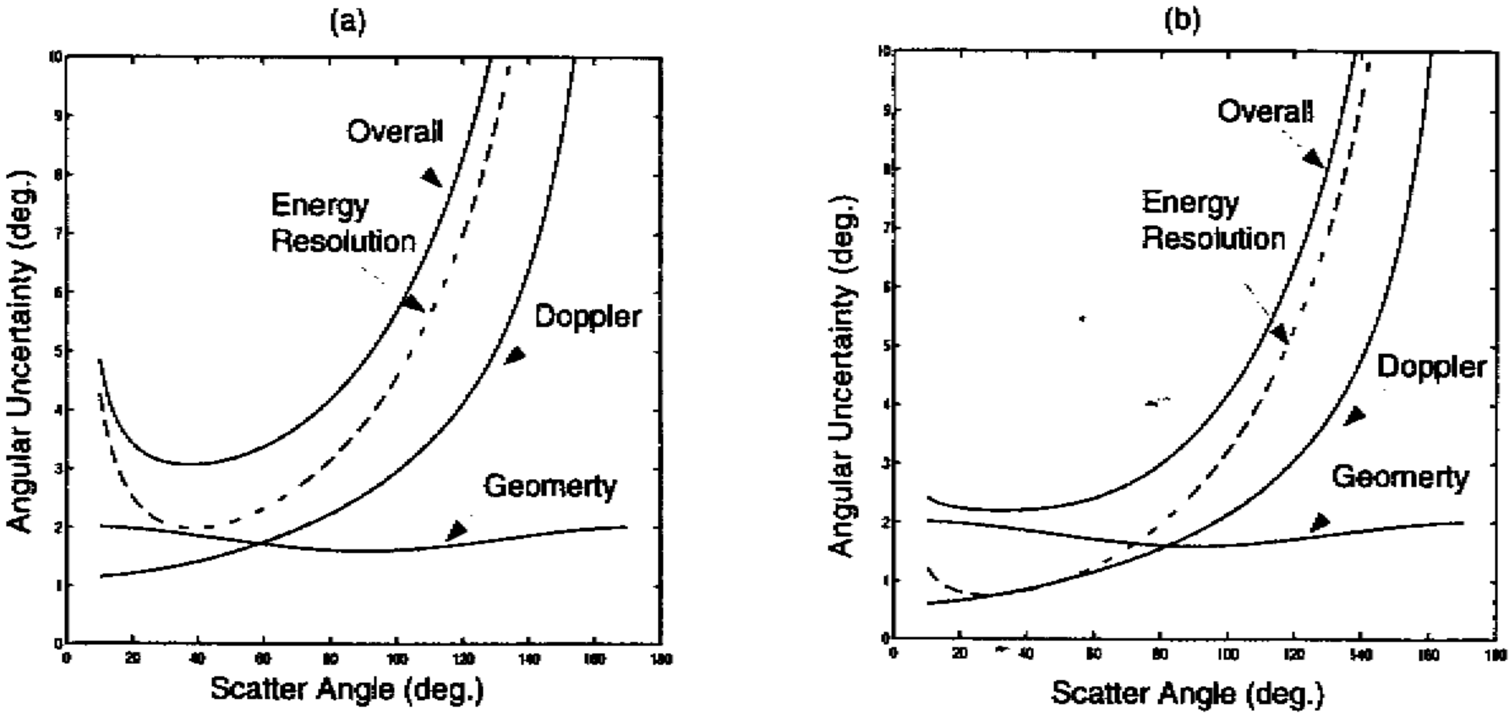


Figure 4. Angular uncertainty estimation. (a) for 511 keV, (b) for 1 MeV.

Du et al. SPIE **3768** p. 228 (1999)

Polarization

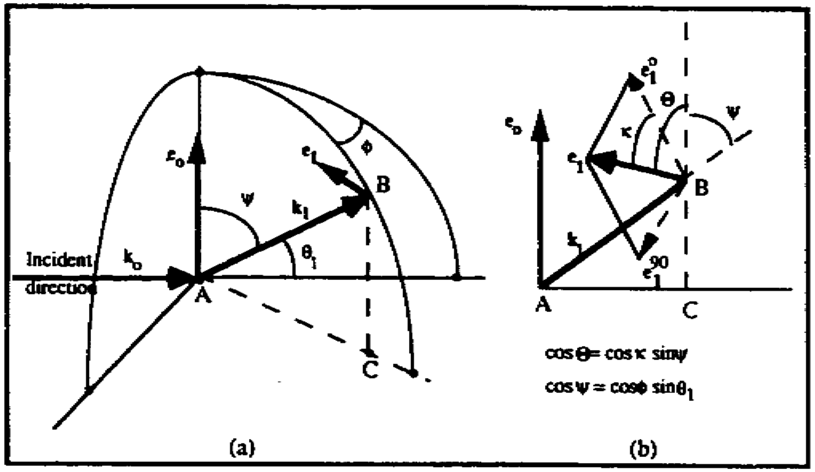
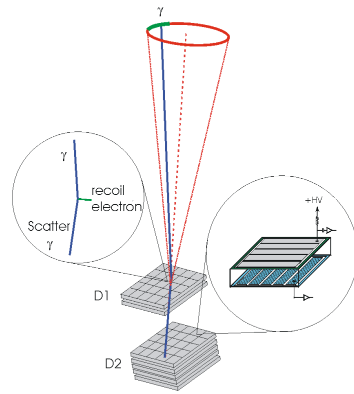


Figure 4.3. (a) The Compton scattering of a polarized gamma ray and (b) enlarged view of polarization vectors in the scattering plane.

Compton scattering cross section is polarization dependent. Compton-scattered gamma rays are polarized (dependent on scattering angle) for an unpolarized incident beam.



Compton Telescopes should make excellent polarimeters.

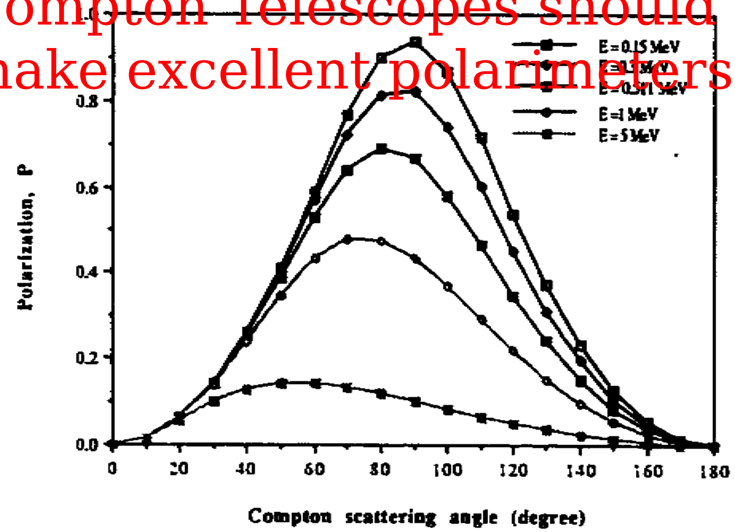
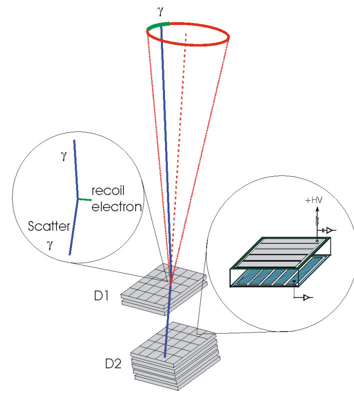


Figure 4.1. Polarization of an initially unpolarized gamma ray beam by Compton scattering process.

Thesis: Multiple Compton Camera for Gamma Ray Imaging

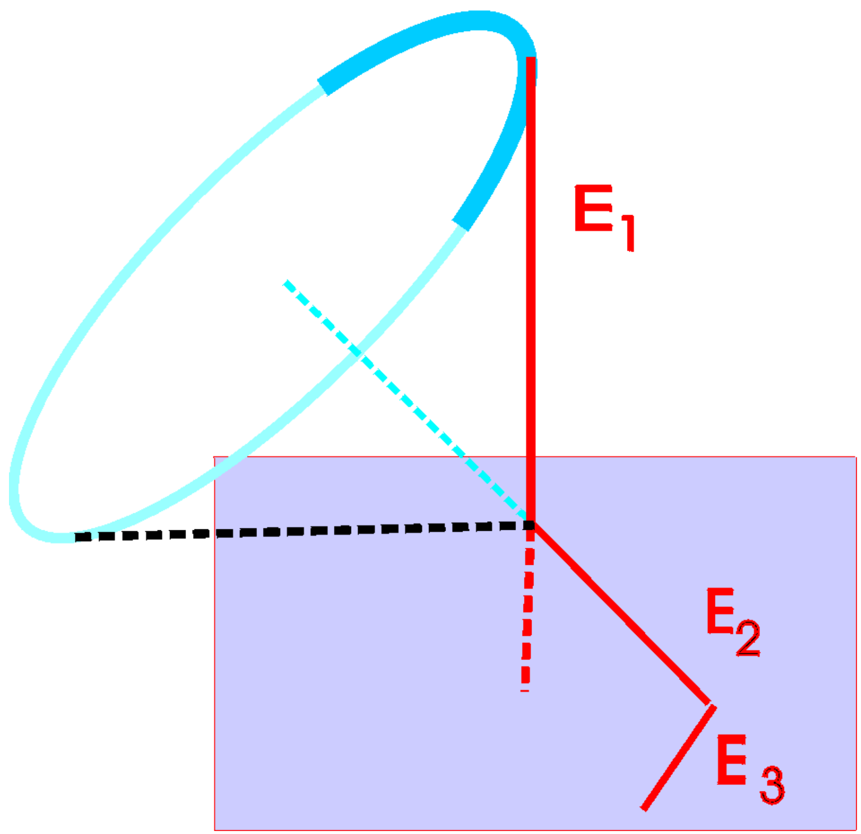
Nesrin Dogan

Univ. Michigan (1993)

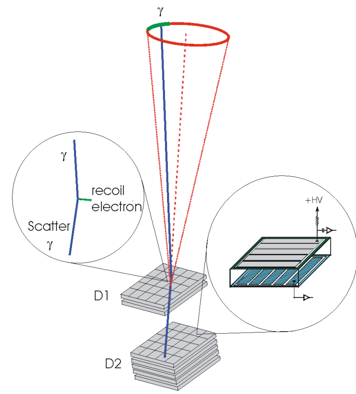


Polarization dependence of the scattering cross section can be used to give higher probability to arcs separated by 180°.

The interaction mean free path through the instrument can be used to give higher weight to one of these arc segments.



Technology Issues



Position-sensitive detectors with excellent energy resolution

- e.g. thick double-sided Silicon strip detectors

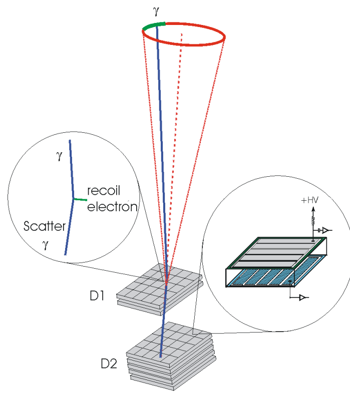
Low-power spectroscopy ASICs

Minimize passive mass in detector volume

Simulations

- Performance vs. ΔE and ΔX
- Attenuation in detector materials (Si, Ge, Xe, Ar)
- Electron tracking modes
- Performance/sensitivity vs. orbit selection
- Impact of electron velocity on ΔE and $\Delta\theta$
- Performance vs. fraction of passive material in detector
- Sensitivity/performance vs. size/configuration of detector

SUMMARY



- Very significant improvements in performance/sensitivity are possible
- 3-Compton scatter concept is very attractive for a high efficiency, high sensitivity instrument
- Potential for dramatic background reduction (see Boggs and Jean; A&A preprint)
- 3-Compton approach appears applicable to all instruments under consideration
- Performance improves dramatically with position and energy resolution